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CAMERON STATION, ALEXANDRIA, VIRGINIA

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Research Report

Precision Time or Frequency Transmission to Moving Vehicles

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Abstract

A circuit is described which is capable of transmitting the output of an ultra-stable oscillator or clock with an extremely high degree of accuracy to a moving vehicle. First-order Doppler frequency shift of the form fv/c, as caused by the velocity of the vehicle relative to the transmitting station, is cancelled, while second-order Doppler of the form fv^2/c^2 is largely eliminated. Because of these features, the circuit makes application of very stable frequency sources to vehicle electronic systems possible to degrees of stability which could previously not be achieved or even approached by several orders of magnitude.

Applications of the circuit include radio navigation, guidance, and tracking, as well as data transmission, telemetry, and possibly communications involving earth satellites, moon satellites, and interplanetary and other space vehicles.

Contents

1. INTRODUCTION

There appears to be a growing need for airborne and space-borne versions of very stable oscillators for various applications like guidance, tracking, navigation, and others . The stability of such oscillators is limited because of the weight and size requirements and the generally hostile environment on board of aircraft and space vehicles caused by vibration, acceleration, also pressure, temperature, and gravitational field variations, etc. The best oscillators presently available for airborne and space applications have long-term stabilities between one part in 10^8 and several parts in 10^{10}, largely dependent on what size and weight can be allocated for these units, and on the particular environment. Laboratory frequency standards, on the other hand, have demonstrated long-term frequency stabilities of the order of one part in 10^{11} and better. These are atomic or molecular resonance oscillators, often referred to as clocks, in a highly controlled environment. Such clocks have been transported by airplane while operating, [1] but here the transport of the operating standard from one point to another was the object of the flight rather than to derive a standard time or frequency for navigation or guidance purposes during the flight.

It can be stated in general terms that ultrastable oscillators are being used on the ground, whereas for airborne and spacecraft use one has to resort to small, lightweight, ruggedized but less stable units. If a particular mission requires a very stable frequency source on board a spacecraft - stable, let us assume, over long periods of time to one part in 10^{11} - then one has to utilize other means.

If the distance between a ground station and the space vehicle is fixed (for example, a satellite in an ideal circular equatorial 24-hour orbit), one could simply transmit a frequency that is derived from the standard to the vehicle where it would arrive at precisely the same frequency, if a stable propagation medium is assumed. If the vehicle is in motion with respect to the ground station, then the frequency arriving at the vehicle is not equal to the transmitted frequency because of Doppler shift.

A system that is capable of transmitting the output of an ultrastable oscillator or clock with an extremely high degree of accuracy to a moving vehicle is described on the following pages.

2. PRECISION TIME OR FREQUENCY TRANSMISSION TO MOVING VEHICLES

Consider two stations, A and B, as depicted in Figure 1. Station A is located on the ground; B is a space vehicle moving at a velocity v relative to A.
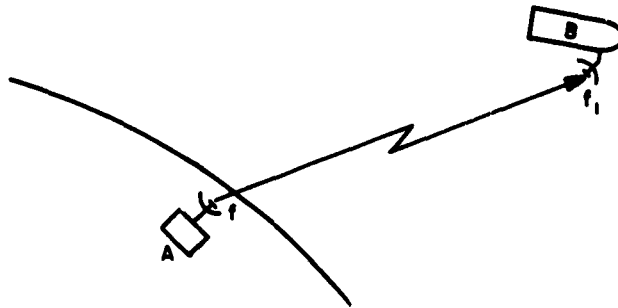

Figure 1

A stable oscillator is operating at A, generating a frequency f. This frequency is transmitted from A. Station B receives $f_1 = f(1 \pm v/c)$ because of the Doppler effect. Factor c is the velocity of light. The sign of the v/c term depends on the direction of motion of B relative to A. It is positive if B moves towards A, and vice versa.

Actually this $(1 \pm v/c)$ factor is an approximation used in place of the correct expression $\pm \sqrt{(v + c)/(c - v)}$. The approximation is very good at velocities much lower than the velocity of light, causing only a second-order error of the form v^2/c^2 and higher-order terms which will be insignificant in many practical cases.

If the velocity of the vehicle relative to Station A is known, f_1 can be corrected at B by adding or subtracting a frequency equal to fv/c in order to produce f. This fv/c term will have to be generated with great accuracy if Doppler shift is to be eliminated effectively, especially in the case of high velocity. An earth satellite,

for instance, with a velocity of 6000 m/sec could experience a Doppler shift of one part in 10^5. If the frequency must be corrected to within one part in 10^{11}, then fv/c must be generated to within one part in 10^6. This seems difficult if not impossible under vehicle-borne conditions. It is therefore advisable to cancel first-order Doppler shift with a circuit, which is described elsewhere[2,3] in detail, as shown in Figure 2. All amplifiers and filters have been omitted.
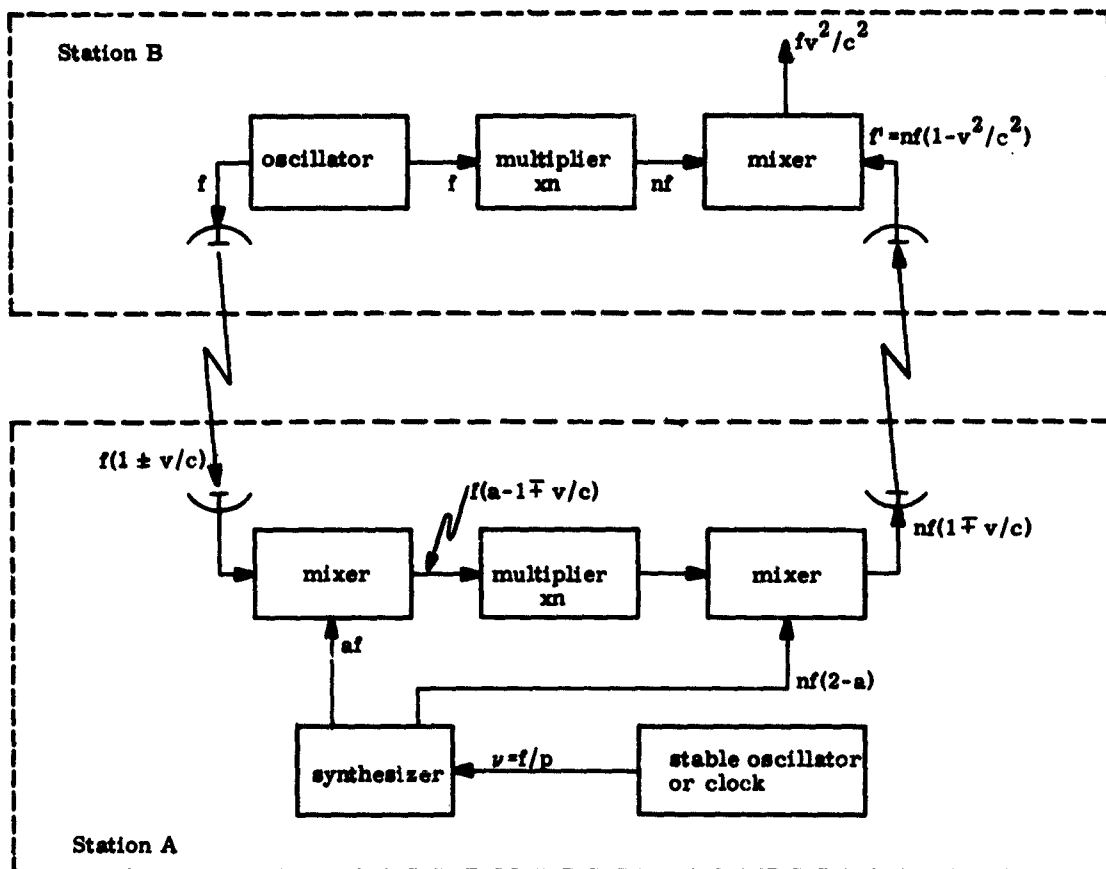
Figure 2

This circuit operates as follows:

Frequency f is generated in the oscillator at the vehicle (Station B) and transmitted. Due to Doppler, $f(1 \pm v/c)$ is received at A and subtracted from af in the first mixer, where $1 < a < 2$. The output of the mixer is amplified and multiplied by n in a multiplier-divider network; n is typically a number close to but not equal to one, like $9/10$, $11/10$, $9/8$, etc. The frequency $nf(2 - a)$ is added in the second mixer to produce $nf(1 \mp v/c)$, which is retransmitted. The two frequencies af and $nf(2 - a)$ are generated from a frequency $\nu = f/p$, a submultiple of f, in a synthesizer

which under certain conditions can be a relatively simple frequency multiplier, as is shown in a practical example in the Appendix.

A very stable oscillator generates ν which is to be transferred to the vehicle. $nf(1 \mp v/c)$ undergoes a Doppler shift while propagating to the vehicle to yield $nf(1 - v^2/c^2)$ at the antenna terminal. This whole process can be expressed in an equation:

$$\left[\{af - f(1 \pm v/c)\}\, n + nf(2 - a) \right] (1 \pm v/c) = nf(1 - v^2/c^2) = f' \tag{1}$$

added in 2nd mixer

transmitted from vehicle

multiplier-divider network

received at vehicle

1st mixer injection frequency

Doppler shift vehicle-to- ground propagation

Doppler shift ground-to-vehicle propagation

Thus the frequency received at the vehicle differs from the frequency transmitted from the vehicle only by a second-order Doppler term, equal to fv^2/c^2, aside from the fact that the frequency f generated at the vehicle has to be multiplied by the factor n before it can be compared to the received frequency. It can also be noted that the v^2/c^2 term has a negative sign, regardless of the sign of the v/c term.

If the frequency of the vehicle-borne oscillator is deviating from f by an amount equal to $\pm\Delta$, then $f(1 \pm \Delta)$ is transmitted and a frequency equal to

$$f' = \left[\{af - f(1 \pm \Delta)(1 \pm v/c)\}\, n + nf(2 - a) \right] (1 \pm v/c) =$$

$$= nf(1 - v^2/c^2) \mp \Delta f(1 \pm 2v/c + v^2/c^2) \tag{2}$$

is received at the vehicle.

At low velocities the v^2/c^2 term can be neglected, and the difference frequency present at the output of the mixer at Station B, equal to the second term in Eq. (2), can be used to generate an error signal in a frequency-voltage transducer (discriminator). This error signal in turn adjusts the frequency of the oscillator until the frequencies that are generated and received at B are equal, and the error signal vanishes. Figure 3 depicts the necessary circuitry at Station B.
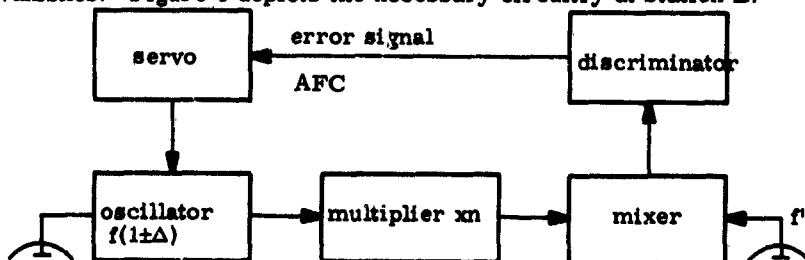

Figure 3

The maximum velocity of Station B relative to Station A at which this circuit can be employed effectively depends on the degree of accuracy and stability of f required at B. Figure 4 graphically represents the first-order and second-order Doppler terms versus the vehicle velocity. It is apparent that the velocity may not be higher than approximately 300 m/sec if the frequency accuracy is to be within or better than one part in 10^{12}, if the circuit described above is used. A maximum velocity of 1000 m/sec can be tolerated for one part in 10^{11} accuracy. For higher velocities and maximum accuracy of the frequency transfer, it becomes necessary to eliminate the second-order Doppler frequency shift. Interplanetary missions, for instance, may encounter velocities of the order of 50,000 m/second. One has to bear in mind that the velocities considered here are always relative to a point on the earth. The earth itself is traveling at a mean velocity of almost 30,000 m/sec in its orbit around the sun, and relative vehicle velocities greater than this can occur under certain conditions. From Figure 4 one will note that for $v = 50,000$ m/sec the second-order Doppler term has a magnitude of 3×10^{-8}. If a frequency is to be transmitted to the vehicle with an accuracy of one part in 10^{11}, which corresponds to the long-term stability of a good laboratory frequency standard, the second-order Doppler shift must be eliminated to within three parts in 10^{4}.

The circuit shown in Figure 3 is capable of correcting the vehicle-generated frequency with great accuracy. The error is approximately equal to fv^2/c^2, which becomes obvious from the following derivation:

$f(1 \pm \Delta)$ is transmitted from the vehicle.

$f(1 \pm \Delta)(1 \pm v/c) = f(1 \pm v/c \pm \Delta \pm \Delta v/c)$ is received at Station A.

$n[2f - f(1 \pm v/c \pm \Delta \pm \Delta v/c)] = nf(1 \mp v/c \mp \Delta \mp \Delta v/c)$ is transmitted from Station A.

$f' = nf(1 \mp v/c \mp \Delta \mp \Delta v/c)(1 \pm v/c) = nf(1 - v^2/c^2) \mp n\Delta f(1 \pm 2v/c + v^2/c^2)$ is received at Station B. f' is subtracted from nf in the mixer at Station B.

The difference frequency is equal to $nfv^2/c^2 \mp \Delta nf(1 \pm 2v/c + v^2/c^2)$.

The circuit in Figure 3 automatically corrects the oscillator frequency until nfv^2/c^2 is equal to $\Delta nf(1 \pm 2v/c + v^2/c^2)$, or

$$\Delta f = f \frac{v^2/c^2}{1 \pm v/c + v^2/c^2} \approx fv^2/c^2. \qquad (3)$$

If the velocity is known within the vehicle at all times, one can generate a bias voltage proportional to v^2/c^2 and add this with the proper amplitude and polarity to the output of the discriminator in Figure 3. The velocity can also be measured and the proper bias be generated automatically with the circuit as shown in Figure 5. It is essentially identical to the circuit in Figure 2 including the modification of Figure 3, with a further modification. A frequency equal to mf is transmitted

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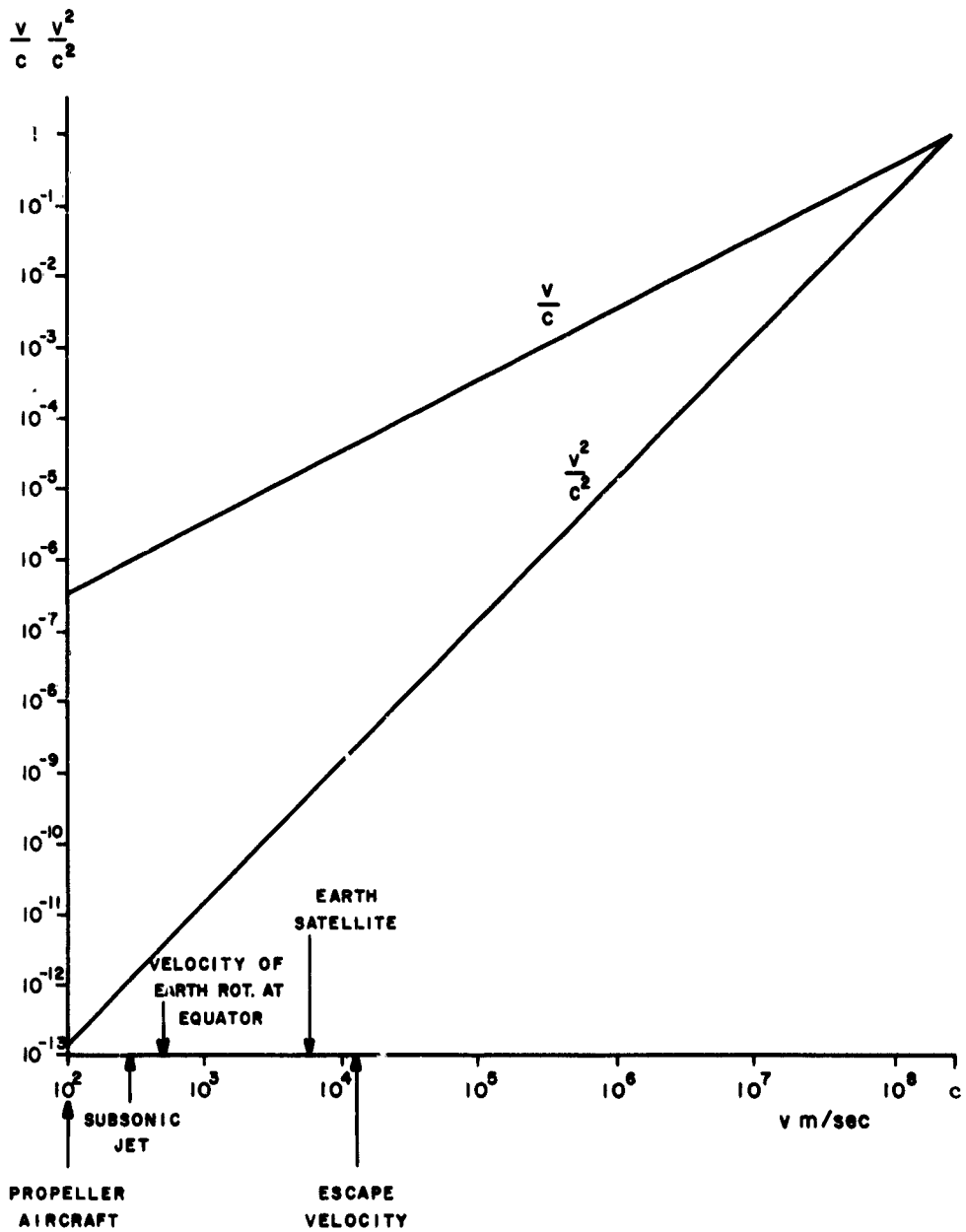
Figure 4

from Station A. It arrives at B as $f'' = mf(1 \pm v/c)$. A mixer with a local oscillator frequency equal to mf as generated at Station B produces a difference frequency

$$mf - mf(1 \pm v/c) = mfv/c. \tag{4}$$

This frequency is detected in a discriminator with a square characteristic, the output of which is proportional to the square of the frequency. This output is used to provide the first discriminator at B with a bias proportional to v^2/c^2. The degree of accuracy with which these operations have to be performed depends upon the relative vehicle velocity v and the accuracy requirement placed on the frequency transfer from A to B.

Figure 5

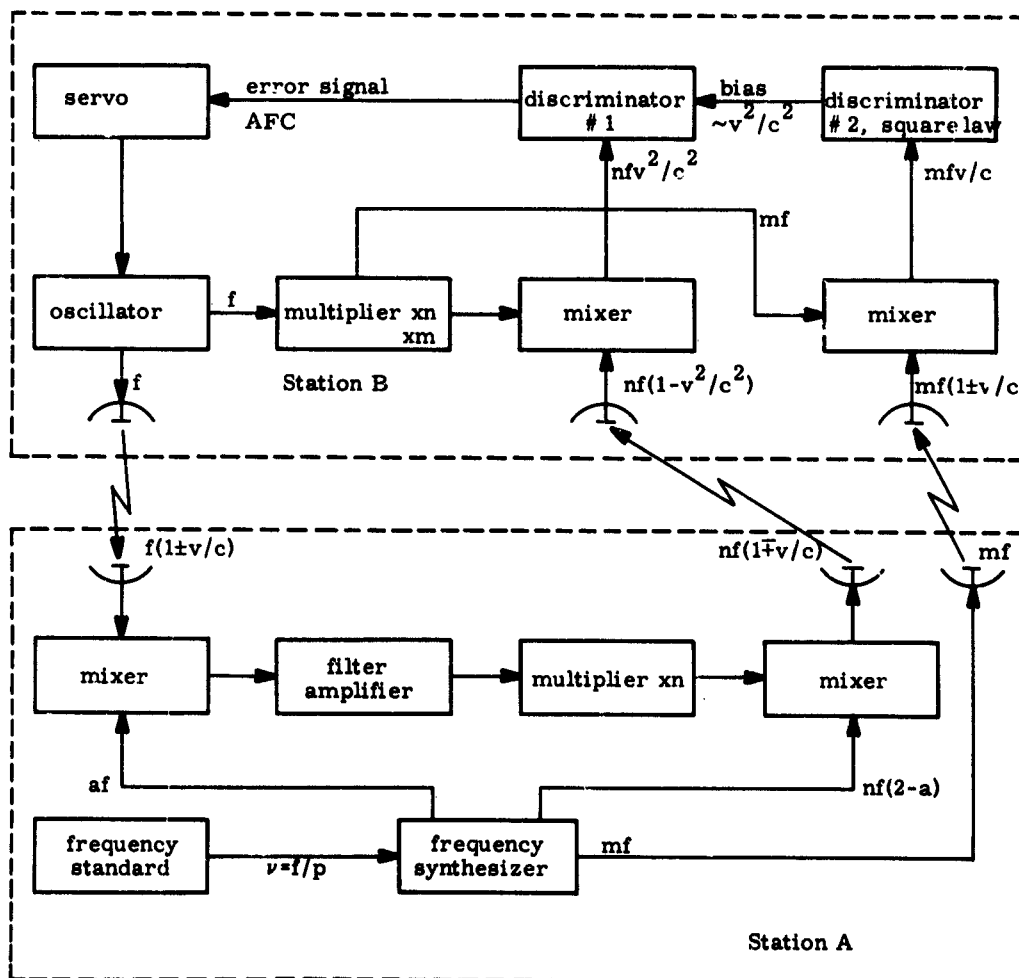The above cited example of $v = 50,000$ m/sec and the accuracy of f being one part in 10^{11}, requires that the bias voltage which is fed to the first discriminator be produced with an accuracy of 3 parts in 10^4. For an earth satellite with $v = 6000$ m/sec and a frequency accuracy requirement of 1 part in 10^{11}, the bias voltage needs to be accurate to only 1 part in 30.

Obviously the accuracy of this circuit is limited. It is not capable of transmitting a frequency accurately within 1 part in 10^{12} if the relative velocity is much higher than 30,000 m/sec because the v^2/c^2 term becomes too large. The v^2/c^2 term can only be compensated for with a maximum accuracy of about 1 part in 10^4 if a circuit as shown in Figure 5 is used. This accuracy can only be increased at the expense of equipment complexity, which is necessarily connected with size and weight increase. The circuit described here is intended to be used with satellites and spacecraft, and its complexity was kept to a minimum while maintaining a very high degree of accuracy consistent with present-day ground-based frequency standard stabilities and interplanetary space vehicle and earth satellite velocities.

At this point it is appropriate to make an estimate of the magnitude of the error that is caused by the earlier used approximation for the Doppler frequency shift, $\sqrt{(c + v)/(c - v)} \approx 1 \pm v/c$. One obtains this expression by expanding $\sqrt{(c+v)/(c-v)}$ into a series, and then dropping all but the first two terms. The third term, incidentally, is equal to $\frac{1}{2}v^2/c^2$. Table 1 gives values for v/c, v^2/c^2, $v/c + \frac{1}{2}v^2/c^2$, and $\sqrt{(c + v)/(c - v)} - 1$ for different velocities. It is apparent from Table 1 that the error introduced by the approximation is very small up to relatively high velocities. At a velocity of 30,000 m/sec, for instance, the error amounts to only $5 \cdot 10^{-5}$, that is $5 \cdot 10^{-5} \cdot v/c = 5 \cdot 10^{-9}$ absolute. The square-law discriminator in Figure 2 can be adjusted to compensate for this error.

Table 1

v m/sec	v/c	v^2/c^2	$v/c + \frac{1}{2}v^2/c^2$	$\sqrt{(c+v)/(c-v)} - 1$
$3 \cdot 10^1$	10^{-7}	10^{-14}	$1.00000005 \cdot 10^{-7}$	$1.00000005 \cdot 10^{-7}$
$3 \cdot 10^2$	10^{-6}	10^{-12}	$1.0000005 \cdot 10^{-6}$	$1.0000005 \cdot 10^{-6}$
$3 \cdot 10^3$	10^{-5}	10^{-10}	$1.000005 \cdot 10^{-5}$	$1.000005 \cdot 10^{-5}$
$3 \cdot 10^4$	10^{-4}	10^{-8}	$1.00005 \cdot 10^{-4}$	$1.000050005 \cdot 10^{-4}$
$3 \cdot 10^5$	10^{-3}	10^{-6}	$1.0005 \cdot 10^{-3}$	$1.0005005 \cdot 10^{-3}$
$3 \cdot 10^6$	10^{-2}	10^{-4}	$1.005 \cdot 10^{-2}$	$1.00505 \cdot 10^{-2}$
$3 \cdot 10^7$	10^{-1}	10^{-2}	$1.05 \cdot 10^{-1}$	$1.055 \cdot 10^{-1}$
$3 \cdot 10^8$	1	1	1.5	∞

The accuracy of this circuit is further limited by the fact that the propagating time from the vehicle to the ground is finite, a fact which has been neglected in the above deductions During a round trip of the signal from the vehicle to the ground and back to the vehicle, the relative velocity might change because of acceleration of the vehicle or rotation of the earth. Equation (1) can be modified to include this case . Recalling Eq. (1):

$$f' = nf(1 - v^2/c^2) \tag{1}$$

which developed from

$$f' = nf(1 \pm v/c)(1 \mp v/c),$$

we introduce

$$f' + \Delta f' = nf(1 \mp v_1/c)(1 \pm v_2/c), \tag{4}$$

where v_1 is the mean velocity of the vehicle relative to the ground during the time the signal is propagating from the vehicle to the ground; v_2 is the respective mean velocity while the signal travels back to the vehicle, and $\Delta f'$ is the deviation of f' caused by the velocity difference. Equation (4) can be developed further as follows:

$$f' + \Delta f' = nf(1 \mp v_1/c \pm v_2/c - v_1 v_2/c^2) . \tag{5}$$

To have f' become equal to nf, or to approach nf to within the required accuracy, the quantity in parentheses must be equal to one or not deviate from one by more than the tolerable inaccuracy. It is therefore obvious that

$$\Delta = |v_1/c| - |v_2/c| - v_1 v_2/c^2 \tag{6}$$

must not be greater than the tolerable inaccuracy of the system. If the second-order Doppler compensating circuit according to Figure 5 is used, a bias proportional to v_2^2/c^2 will be added, and Δ reduces to

$$\Delta = |v_1/c| - |v_2/c| - v_1 v_2/c^2 + v_2^2/c^2 = |v_1/c| - |v_2/c| - v_2(v_1 - v_2)/c^2 \tag{7}$$

The last term in Eq. (7) is very small as compared with the first two terms. It becomes apparent that the error caused by a velocity variation during the propagation round-trip time can become rather significant, because first-order Doppler

of the form fv/c is not effectively cancelled any more.

A potentially very large source of relative velocity variation is the earth itself. A point on the equator moves at a velocity of 463 m/sec because of rotation of the earth. The velocity v of a vehicle, which is traveling at a velocity v' relative to the center of the earth in the earth's equatorial plane, is therefore varying according to Eq. (8), provided that the distance is much larger than the earth radius (Figure 6).

$$v = v' + 463 \sin \frac{2\pi}{86400} t \qquad \text{m/sec, t in sec.} \qquad (8)$$

$$\omega = \frac{2\pi}{86400}$$
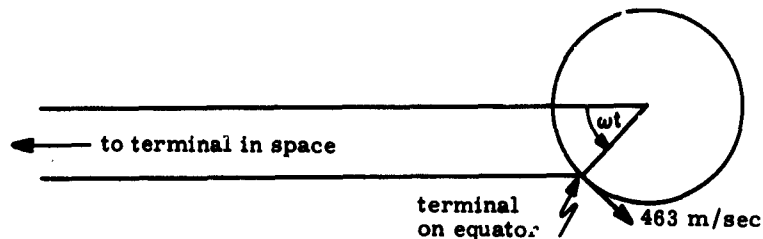

to terminal in space

terminal on equator

463 m/sec

Figure 6

The velocity variation is largest when the derivative of $\sin \omega t$, which is $\cos \omega t$, is at a maximum. This occurs when ωt equals zero. The error Δ as caused by the rotation of the earth can be evaluated by combining Eqs. (6) and (8).

$$\Delta = \frac{2 \cdot 463 \sin \omega t}{c} - \frac{v'^2 - 463^2 \sin^2 \omega t}{c^2} \quad . \qquad (9)$$

Equation (9) reveals the fact that, to a first-order approximation, Δ is not dependent upon the relative velocity of the vehicle, but rather on the angle ωt which is proportional to the propagation time and the distance between the ground and space stations.

Under certain conditions, Δ can assume fairly large values. Let us assume a practical case. A vehicle is located at a range of $4.5 \cdot 10^{10}$ m, which is about equal to the distance Earth-Venus during the first Millstone Hill radar contact in 1959. The round-trip duration for a radio signal is 5 minutes at this range, during which time the earth rotates 1.25°. The largest velocity variation according to Eq. (8) occurs at or near 0°, or in this case between -0.625° and +0.625°. For the

duration of propagation to the earth an average value for ωt of $0.3125°$ is assumed. The value for the first term in Eq. (9) turns out to be $1.68 \cdot 10^{-8}$ and, considering a relative velocity v of $50,000$ m/sec, Δ is equal to $1.1 \cdot 10^{-8}$. This assumed case is highly unfavorable because a vehicle at very great range and traveling at extremely high velocity in the equatorial plane of the earth was considered, while a vehicle in the vicinity of the planet Venus must not necessarily be in the earth's equatorial plane because of the inclination of the axis of the earth with respect to its orbital plane. If the vehicle is located at a point on the axis of the earth (above the North or South Pole), the effect of the velocity variation due to the rotation of the earth would vanish. The same can be effected by locating the ground station at the North or South Pole. This is of course rather impractical, but one can minimize the effect by placing the ground station at a high latitude.

Equations (8) and (9) can be modified to take the elevation angle of the vehicle above the equatorial plane of the earth and the latitude of the ground station into account, as presented in Eqs. (10) and (11):

$$v = v' + 463\cos\alpha\cos\beta\sin\omega t \tag{10}$$

$$\Delta = \frac{2 \cdot 463\cos\alpha\cos\beta\sin\omega t}{c} - \frac{v'^2 - 463^2\cos^2\alpha\cos^2\beta\sin^2\omega t}{c^2}, \tag{11}$$

where α and β are the latitude of the ground station and the elevation of the vehicle above the earth's equatorial plane, respectively.

Equation (12) is obtained by combining Eqs. (7) and (10) to consider the second-order Doppler compensating feature of the circuit according to Figure 5.

$$\Delta = \frac{2 \cdot 463\cos\alpha\cos\beta\sin\omega t}{c} - \frac{2 \cdot 463\cos\alpha\cos\beta\sin\omega t(v' - 463\cos\alpha\cos\beta\sin\omega t)}{c^2} \tag{12}$$

Inspection of Eq (12) reveals the fact that the second term is proportional to v/c^2 rather than v^2/c^2 in Eq. (11), which does not consider reduction of second-order Doppler.

It should also be pointed out that the effect of the earth rotation is equal to zero, to a first-order approximation, if averaged over a 24-hour period. Furthermore, since the effect is a function of the location of the space station, the latitude of the ground station, and the time of day, it is even possible to reduce this effect considerably by introducing a bias signal, which takes all these factors into account, into Discriminator 1 in Figure 5. A relatively simple computer would be required to generate the necessary bias. The accuracy involved would not have to be excessively great. If the effect of the earth's rotation is, for instance, 10^{-9}

and the required accuracy of the transmitted frequency is 10^{-11}, then the bias signal which is to correct for the rotation of the earth has to be generated with an accuracy of 10^{-2} or one part in 100. Only linear, sine, and cosine functions are involved. Sine and cosine functions compensating for earth rotation can be generated by means of a 24-hour clock coupled to a potentiometer. The 24-hour clock can possibly be driven synchronously by a frequency that is derived from the standard frequency transmitted to the vehicle.

Let us consider a second example. An earth satellite is in a circular orbit in the equatorial plane of the earth at a distance of 375,000 km, which is approximately equal to the mean distance to the moon. The ground station is at 60° latitude. The time for round-trip propagation is equal to

$$\frac{375,000 \text{ km} \cdot 2}{300,000 \text{ km/sec}} = 2.5 \text{ sec.}$$

In Eqs. (11) and (12), $t = 2.5/4 = 0.625$ sec is used to obtain the mean angle ωt. Velocity v' is equal to zero in a circular orbit. Δ turns out to be $6.8 \cdot 10^{-11}$ in both Eqs. (11) and (12), because only the first terms, which are equal in both equations, are significant. Δ, in this example, can be corrected by feeding a bias proportional to $\sin \omega t$, of the proper polarity and magnitude, into Discriminator 1 in Figure 5. This bias does not have to be very precise. For a frequency transmission accurate to 1 part in 10^{11}, the bias must be accurate to one part in 6.8 or about 15 per cent. It could easily be generated by means of a clock driving a potentiometer.

The above derivations and examples serve to show that the effect of the rotation of the earth, together with large distances between earth and vehicle and the associated long propagation times, can produce a significant error in the frequency of the signal transmitted to the vehicle. Equations (6) and (7) hold for the specific cases treated, as well as for the case where the relative velocity varies because of an acceleration of the vehicle. To evaluate this situation, one must modify Eqs. (8) through (12) to include the velocity variation due to the acceleration of the vehicle, in addition to the effect of the earth rotation.

It is also apparent from the above examples that the effect of velocity variation on the frequency of the transmitted signal can be corrected by relatively simple means, even in the case of great ranges like Earth-Venus, and very high velocities of the order of 50,000 m/second.

3. CONCLUSION

On the preceding pages, a circuit is described which is suitable for transmitting a signal to a moving vehicle. The frequency of the signal is largely unaffected by

relative uniform or accelerated motion of the vehicle with respect to the ground station. The frequency can be transmitted with an accuracy exceeding one part in 10^{12} at velocities and distances consistent with earth satellites and interplanetary probes. First-order Doppler frequency shift of the form fv/c is automatically cancelled, while second-order Doppler of the form fv^2/c^2 is reduced by several orders of magnitude.

The circuit performs the cancellation of Doppler shift automatically. For the Doppler cancelling feature, the signal must make a complete round trip from Station A, the ground station, to Station B at the vehicle, and back to Station A. To eliminate the fv^2/c^2 term, it is necessary that the velocity is known at the vehicle.

If the relative vehicle velocity during propagation from Station A to B is different from the relative velocity during propagation from B to A, for a complete round trip of the signal, due to acceleration of either one or both of the stations, the accuracy of the frequency transmitted to Station B is degraded. This effect can be reduced by several orders of magnitude by means of a modification of the described circuit, if the acceleration function is known.

With the above-mentioned features, the circuit makes frequency sources available within the moving vehicle, with the accuracy and stability of atomic or molecular standard-frequency oscillators. The standard oscillator itself can be ground-based, in the necessary controlled environment. Only simple amplifiers, oscillators, filters, mixers, etc., which can be ruggedized easily, are in the vehicle.

References

1. Reder, F. H., "Results of a Long-Range Clock Synchronization Experiment," *Proceedings of the IRE* (June 1961).

2. Waetjen, R. M., "Cancellation of Doppler Frequency Shift," Invention Disclosure No. 8937, AFCRL, (Oct 1961).

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Appendix

The following practical example is chosen to illustrate possibilities for the design of circuitry at Station A.

In order to minimize effects of frequency-dependent propagation anomalies, n is chosen close to 1, in this example equal to 7/8. Frequency f = 240 Mc, nf = 210 Mc, a = 14/13. The frequency at the output of the first mixer at Station A is equal to $(14/13 - 1)f = f/13 = 18.46$ Mc which can be divided by eight and multiplied by seven by fairly conventional techniques. The frequency at the output of the times-n network is equal to $7f/13 \cdot 8 = 16.15$ Mc which is brought to the second mixer. Here $nf(2 - a) = 21f/26$ is added and 7/8 times f is obtained. In this case the frequency synthesizer would be quite simple (Figure 7). The output of the frequency standard operating at $(1/26)f = 9.23$ Mc is multiplied by seven and yields $7f/26 = 64.615$ Mc. Multiplying this by four yields the first mixer injection frequency, $14f/13 = 258.46$ Mc, and the injection frequency for the second mixer through multiplication by three, $21f/26 = 193.85$ Mc.
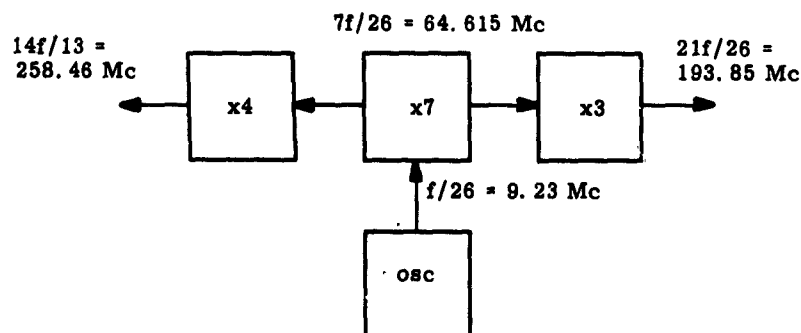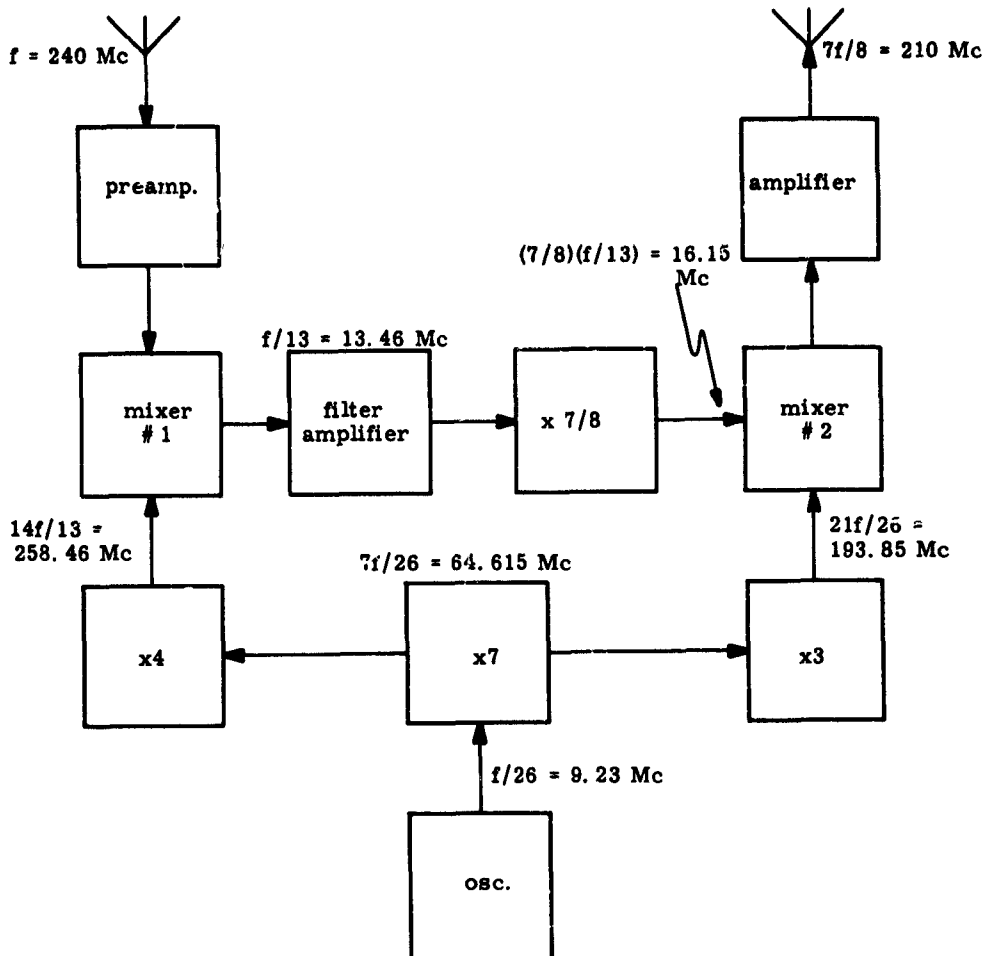

Figure 7

Figure 8.

The block diagram in Figure 8 depicts the complete circuit at Station A for the chosen example.

In several cases it will not be necessary to have transmitted and received frequencies close together to avoid frequency shifts due to propagation anomalies. Such shifts would be very small at microwave frequencies, if at all present, and probably negligible in many instances. If the ground-to-vehicle frequency is a multiple of the vehicle-to-ground frequency, the circuit simplifies considerably because frequency division is not necessary. The factor n would be an integer. The circuit simplifies even more if the mixer injection frequencies in Figure 8 are equal. For n = 2, for instance, this is the case if a = 4/3; and for n = 3, a has to be equal to 3/2.